Azacalix[4]arene cation radicals: spin-delocalised doublet- and triplet-ground states observed in the macrocyclic *m*-phenylene system connected with nitrogen atoms†

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Electron paramagnetic resonance spectroscopy has unmasked for the first time the spin-delocalised doublet- and triplet-ground states of azacalix[4]arene cation radicals.

Calixarenes have been attracting much attention not only in supramolecular chemistry[1] but also in the chemistry of molecular magnetism because the 1,3-phenylene moiety acts as a ferromagnetic coupler.[2] While a variety of calixarene-based polyradicals in a high-spin ground state have thus far been synthesised,[3] the instability inherent in the carbon-based radicals places an obstacle to greater access to organic magnetic materials. Replacement of the bridging carbons of calixarenes with nitrogen atoms is of great interest because the bridging nitrogen atoms can offer more stable spin-bearing sites than the electronically less negative carbon bridges.[4] However, no precedent exists for the observation of high-spin states of nitrogen-bridged calixarene radicals, though Tanaka and co-workers have theoretically predicted that deoxyazacalix[4]arene **1** is accessible to a high-spin ground state upon oxidation.[5] Recently, we independently reported the synthesis and molecular structure of azacalix[4]arene **2** with a 1,3-alternate conformation in solution and in the solid state (Fig. S1, ESI†).[6] A DFT study indicates that model compound **3** has four quasi-degenerate non-bonding molecular orbitals (Fig. S3, ESI†). Therefore, it is conceivable that, if we remove electrons from this molecule, the resultant radical species exists in a high-spin ground state. To elucidate the feasibility of applying azacalixarenes to high-spin materials, we have investigated the oxidation behaviour of azacalix[4]arene **2** and the spin-state of the oxidised species. In this communication, we report the first and successful observation of the spin-delocalised doublet- and triplet-ground states of the cationic radicals of **2** (Chart 1).

Electrochemical measurements of **2** and reference compounds **5**, **6** and **7** were carried out in CH_2Cl_2 containing 0.1 M Bu_4NClO_4 as supporting electrolyte. As shown in Fig. 1, the cyclic voltammogram of **2** consisted of two reversible one-electron oxidation waves at $E = +0.14$ and $+0.45$ V (*vs.* Fc/Fc^+), which correspond to the removal of an electron from

1: X = Y = Z = H
2: X = *t*-Bu, Y = OMe, Z = Me
3: X = Me, Y = OMe, Z = Me
4: X = Y = H, Z = Me
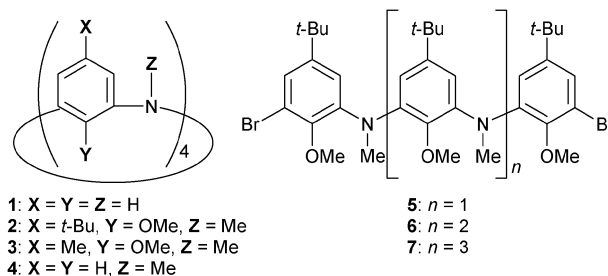
5: *n* = 1
6: *n* = 2
7: *n* = 3

Chart 1

each of two bridging nitrogen atoms. This two-electron redox process of **2** was almost reversible even after voltammetric scans were repeated 10 times, as shown in Fig. S7 (ESI†). Another oxidation wave, though irreversible, was observed at a higher potential up to +1.0 V (Fig. S8a, ESI†), illustrating the instability of further oxidised species on the examined voltammetric time scale. Similarly, the reference compounds **5**–**7** exhibited two oxidation waves with potentials given in Table 1, but only the first oxidation process was reversible in these compounds (Fig. S8b–d, ESI†). The oxidation behaviour of **2** differs greatly from that of analogous deoxyazacalix[4]-arene **4** which yields no stable oxidised species,[5] suggesting that introduction of sterically bulky *tert*-butyl and methoxy groups contribute to the radical stability of $2^{•+}$ and $2^{2(•+)}$.[7] It is interesting to note that E_1^{ox} of **2** is more than 0.20 V lower than those of acyclic compounds **5**–**7**. The enhanced electron donor ability of **2** results from its cyclic framework, by which spin density of the monocationic species $2^{•+}$ is distributed
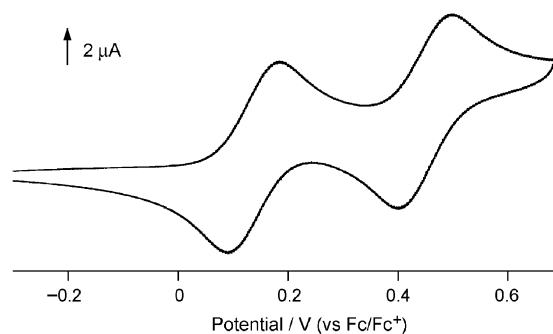
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† Electronic supplementary information (ESI) available: Full experimental details for the syntheses of compounds **5**–**7**, DFT calculations, electrochemical measurements and variable-temperature EPR measurements. See DOI: 10.1039/b801127c
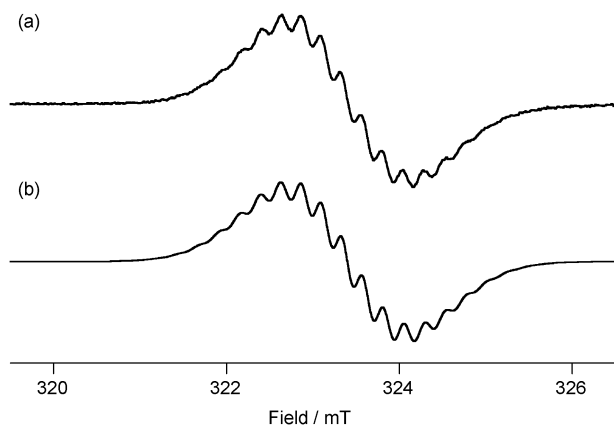

Fig. 1 Cyclic voltammogram of azacalix[4]arene **2** (1 mM) in CH_2Cl_2–Bu_4NClO_4 (0.1 M) at 298 K, scan rate 100 mV s^{-1}, potential calibrated against Fc/Fc^+.

Table 1 Oxidation potentials of azacalix[4]arene **2** and the reference compounds **5–7**[a]

Compound	E_1^{ox}	E_2^{ox}
2	0.14	0.45
4	0.31^{bc}	—
5	0.50	0.85^c
6	0.37	0.61^c
7	0.36	0.58^c

[a] Conditions: $[\mathbf{2}] = [\mathbf{5}] = [\mathbf{6}] = [\mathbf{7}] = 1$ mM, 0.1 M Bu_4NClO_4 in CH_2Cl_2, potentials *versus* Fc/Fc^+, 298 K, scan rate 100 mV s^{-1}. [b] Cited from ref. 5. [c] Anodic potential.

over the molecular framework, as revealed by EPR study described below.

EPR measurement was performed for the monocation radical $\mathbf{2}^{\bullet+}$, which was generated *in situ* by electrochemical oxidation of **2** (1 mM) at +0.30 V.‡ As shown in Fig. 2(a), the EPR spectrum of $\mathbf{2}^{\bullet+}$ in CH_2Cl_2 containing 0.1 M Bu_4NClO_4 at 223 K exhibited a multiplet signal with around 15 lines at $g = 2.0034$. The spectrum was reproduced by the simulation analyses (Fig. 2(b) and S9, ESI†), demonstrating that the unpaired spin was delocalised over the molecular framework of $\mathbf{2}^{\bullet+}$. In other words, the spin was distributed throughout the four bridging nitrogen atoms and the four aromatic rings of $\mathbf{2}^{\bullet+}$, as supported by a DFT calculation on the model compound $\mathbf{3}^{\bullet+}$ (Fig. S4, ESI†). The observed spin-delocalisation would be due to the intramolecular charge transfer between the redox centres as in the case of the *m,p*-linked polyaniline systems.[8] Such spin-delocalisation over the cyclic framework of $\mathbf{2}^{\bullet+}$ leads to a decrease in spin density per aromatic carbon *ortho* to the nitrogen bridges. Besides, the bulky *tert*-butyl and methoxy groups effectively protect those aromatic carbon atoms against an attack by solvent molecules and/or other molecules eventually inducing undesirable decomposition. Accordingly, the observed radical stability of $\mathbf{2}^{\bullet+}$ is ascribed to a combination of the spin-delocalisation and the steric protection of the reactive sites.
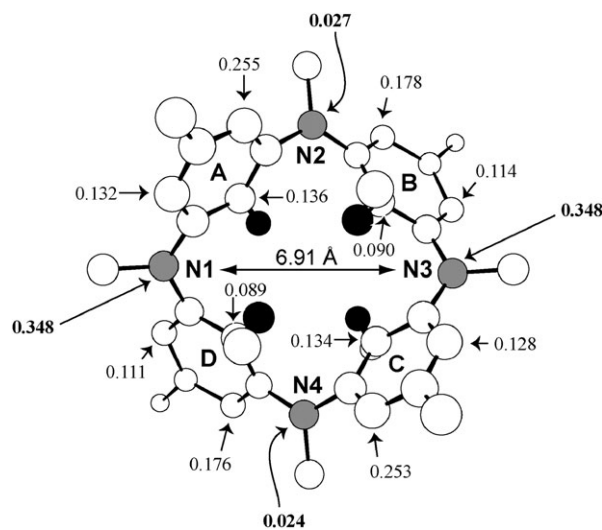

Fig. 3 EPR spectrum of dication radical $\mathbf{2}^{2(\bullet+)}$ observed at 100 K in the CH_2Cl_2 glass containing 10% (v/v) trifluoroacetic acid. Inset: the half-field resonance for the forbidden transition ($\Delta M_s = \pm 2$).

Dication radical $\mathbf{2}^{2(\bullet+)}$ was also characterised by means of EPR spectroscopy. Chemical oxidation of **2** (5 mM) with 2 equiv. of phenyliodine(III) bis(trifluoroacetate)[9] at ambient temperature for 5 min in CH_2Cl_2 containing 10% (v/v) trifluoroacetic acid gave a dark-blue solution of $\mathbf{2}^{2(\bullet+)}$, which survived at this temperature for more than 10 min. Once the solution was frozen, no detectable decomposition of $\mathbf{2}^{2(\bullet+)}$ was observed at least during EPR measurement. Fig. 3 shows the EPR spectrum of $\mathbf{2}^{2(\bullet+)}$ in the solvent glass at 100 K. There appeared four broad lines characteristic of zero-field splitting with an axial symmetry. Half-field resonance for the forbidden transition ($\Delta M_s = \pm 2$) was also observed, clearly indicating that dication radical $\mathbf{2}^{2(\bullet+)}$ existed in a triplet state. The zero-field splitting parameter $|D|$ was determined to be 6.9 mT, from which an average distance between the two radical centres was estimated to be 7.4 Å according to the point-dipole approximation. This calculated distance is close to the distance of 6.91 Å between two diagonal nitrogen atoms of neutral species **2** (Fig. S1b, ESI†). A further insight into the structural and electronic properties of $\mathbf{2}^{2(\bullet+)}$ was provided by a DFT calculation on the model compound $\mathbf{3}^{2(\bullet+)}$. Fig. 4 and

Fig. 2 (a) EPR spectrum of azacalix[4]arene cation radical $\mathbf{2}^{\bullet+}$ observed at 223 K in CH_2Cl_2 containing 0.1 M Bu_4NClO_4. (b) Simulated EPR spectrum with the following parameters: $A_N = 0.200$ mT (for the four equivalent nitrogen atoms), $A_{NCH_3} = 0.255$ mT (for the twelve equivalent *N*-methyl hydrogen atoms), $A_{ArH} = 0.247$ mT (for the eight equivalent aromatic hydrogen atoms), and simulation line width = 0.18 mT.

Fig. 4 The optimised structure and the selected spin densities of model compound $\mathbf{3}^{2(\bullet+)}$ in a triplet state calculated at a B3LYP/6-31G**//B3LYP/6-31G** level.

S5, ESI† display the optimised structure and the selected spin densities of $3^{2(\bullet +)}$. In this model, the spins are mainly distributed to the two diagonal nitrogens (N1 and N3) and four phenyl rings (ring A, B, C and D), and the separation distance of 6.91 Å between N1 and N3 is close to the calculated distance of 7.4 Å between two radical centres of $2^{2(\bullet +)}$ mentioned above. Interestingly, the other nitrogen atoms N2 and N4 of $2^{2(\bullet +)}$ retain almost no spin density, implying that dication radical $2^{2(\bullet +)}$ can be viewed as a cyclic array of two diphenylamine-type cation radicals[10] connected with nitrogen atoms N2 and N4.

To further explore whether the observed triplet state of $2^{2(\bullet +)}$ was a ground or thermally excited state, variable-temperature EPR experiments were performed in the range of 4.5 to 100 K. As shown in Fig. S10 (ESI†) the signal intensity for the forbidden transition ($\Delta M_s = \pm 2$) increased with the decrease in temperature, indicating that dication radical $2^{2(\bullet +)}$ existed either in a triplet ground state or in a degenerate state of triplet and singlet states. In a DFT calculation, the model compound $3^{2(\bullet +)}$ favors a triplet ground state over a singlet state by an energy gap (ΔE_{S-T}) of 10.0 kcal mol^{-1}, demonstrating that the dication radical $2^{2(\bullet +)}$ exists in a triplet ground state. The observed ferromagnetic interaction in $2^{2(\bullet +)}$ is noteworthy because antiferromagnetic interaction *via* "superexchange" interaction[11] have been reported in similar but acyclic spin systems[12] such as A–Y–X–Y–A, where A, X and Y represent the localised doublet species, heteroatom (lone-pair) and *m*-phenylene moiety, respectively. The "superexchange" interaction depends on the geometry, particularly dihedral and torsion angles around the heteroatom.[13] In the DFT-optimised $3^{2(\bullet +)}$ (Fig. 4 and S5, ESI†), the dihedral angles between the two phenyl rings A/B and C/D were calculated to be 71.3 and 71.4°, respectively, and the average torsion angles $\angle C(sp^2)$–N–$C(sp^2)$–$C(sp^2)$ around N2 and N4 were 41.5 and 41.7°, respectively. These structural parameters indicate that the bridging nitrogen atoms N2 and N4 experience severe out-of-plane twisting. Accordingly, it is reasonable to conclude that the unusual ferromagnetic interaction observed in $2^{2(\bullet +)}$ is ascribed to the twisted geometry at the bridging nitrogens.[13]

In summary, we have demonstrated that a high-spin ground state is attainable in azacalix[4]arene system. The first and successful observations of the triplet and doublet states of **2** were ensured by the radical stability arising from a combination of steric protection and spin-delocalisation. In addition, a cyclic but non-planar framework of **2** is crucial to render the bridging-nitrogen a ferromagnetic coupler rather than an antiferromagnetic coupler. These findings in **2** would be applicable to its analogous systems with larger ring size and thus with the promising potential for higher-spin states. Investigations along this line are now in progress.

Notes and references

‡ Chemical oxidation of **2** (1 mM) with 0.9 equiv. of phenyliodine(III) bis(trifluoroacetate)[9] in CH$_2$Cl$_2$ afforded the identical EPR spectrum with that of Fig. 2(a).

1. (*a*) C. D. Gutsche, *Calixarenes Revisited*, ed. J. F. Stoddart, Royal Society of Chemistry, Cambridge, 1998; (*b*) *Calixarenes 2001*, ed. Z Asfari, V Böhmer, J Harrowfield, J Vicens and M Saadioui, Kluwer, Dordrecht, 2001.
2. (*a*) H. Iwamura, *Adv. Phys. Org. Chem.*, 1990, **26**, 179; (*b*) D. A. Dougherty, *Acc. Chem. Res.*, 1991, **24**, 88; (*c*) H. Iwamura and N. Koga, *Acc. Chem. Res.*, 1993, **26**, 346; (*d*) A. Rajca, *Chem. Rev.*, 1994, **94**, 871; (*e*) A. Rajca, *Adv. Phys. Org. Chem.*, 2005, **40**, 153.
3. (*a*) K. Matsuda, N. Nakamura, K. Takahashi, K. Inoue, N. Koga and H. Iwamura, *J. Am. Chem. Soc.*, 1995, **117**, 5550; (*b*) S. Rajca, A. Rajca, J. Wongsriratanakul, P. Butler and S.-M. Choi, *J. Am. Chem. Soc.*, 2004, **126**, 6972, and references therein.
4. A. R. Forrester, *Organic Chemistry of Stable Free Radicals*, Academic Press, New York, 1968.
5. A. Ito, Y. Ono and K. Tanaka, *J. Org. Chem.*, 1999, **64**, 8236.
6. (*a*) H. Tsue, K. Ishibashi, H. Takahashi and R. Tamura, *Org. Lett.*, 2005, **7**, 2165; (*b*) H. Tsue, K. Ishibashi, S. Tokita, K. Matsui, H. Takahashi and R. Tamura, *Chem. Lett.*, 2007, **36**, 1374; (*c*) H. Tsue, K. Ishibashi and R. Tamura, in *Heterocyclic Supramolecules*, ed. K Matsumoto, Topics in Heterocyclic Chemistry, Springer-Verlag, Berlin–Heidelberg, in press.
7. M. Yano, K. Sato, D. Shiomi, A. Ichimura, K. Abe, T. Takui and K. Itoh, *Tetrahedron Lett.*, 1996, **37**, 9207.
8. (*a*) M. M. Wienk and R. A. J. Janssen, *J. Am. Chem. Soc.*, 1997, **119**, 4492; (*b*) Y. Hirao, A. Ito and K. Tanaka, *J. Phys. Chem. A*, 2007, **111**, 2951; (*c*) X. Z. Yan, J. Pawlas, T. Goodson III and J. F. Hartwig, *J. Am. Chem. Soc.*, 2005, **127**, 9105.
9. L. Eberson, M. P. Hartshorn and O. Persson, *Acta Chem. Scand.*, 1995, **49**, 640.
10. F. A. Neugebauer and S. Bamberger, *Angew. Chem., Int. Ed. Engl.*, 1971, **10**, 71.
11. (*a*) P. W. Anderson, *Phys. Rev.*, 1950, **79**, 350; (*b*) P. J. Hay, J. C. Thibeault and R. Hoffman, *J. Am. Chem. Soc.*, 1975, **97**, 4884; (*c*) T. Nakamura, T. Momose, T. Shida, K. Sato, S. Nakazawa, T. Kinoshita, T. Takui, K. Itoh, T. Okuno, A. Izuoka and T. Sugawara, *J. Am. Chem. Soc.*, 1996, **118**, 8684; (*d*) T. Itoh, K. Matsuda and H. Iwamura, *Angew. Chem., Int. Ed.*, 1999, **38**, 1791.
12. S. Suchada and A. Rajca, *J. Am. Chem. Soc.*, 1995, **117**, 9172.
13. K. Matsuda, T. Yamagata, T. Seta, H. Iwamura and K. Hori, *J. Am. Chem. Soc.*, 1997, **119**, 8058.